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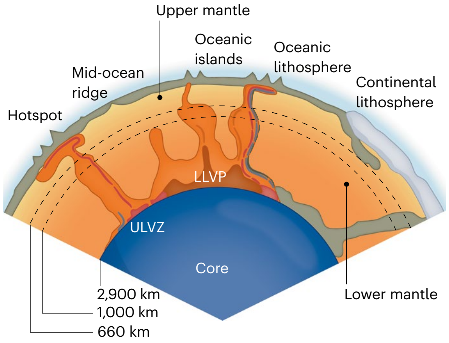
The ultra-lowdown on mantle heterogeneity

Compositional and structural variations within Earth's lower mantle are a complex puzzle to which seismic data hold clues.

The theory of plate tectonics offers answers about how mantle convection interacts with crust at the Earth's surface, but many questions about the mantle's composition and structure at depth remain unanswered. Earthquakes release energy in the form of P- and S-waves that travel through Earth's interior. Travel times of these seismic waves from source to receiver can be used to infer the properties of the material the waves have passed through. Seismic tomography is the most effective method for imaging the Earth's interior and investigating the lower mantle below 1,000 km depth. Seismic waves at the base of the mantle are distorted and deflected by velocity anomalies, revealing seismic heterogeneities and abnormally slow areas due to a complex lower mantle structure[1]. In this issue and an accompanying Collection of recent research from across the Nature Portfolio, we highlight how the increasing availability of higher-resolution large-scale seismic imaging arrays, as well as improved analytical and numerical simulation techniques, are yielding insights into these enigmatic structures.

As Lauren Waszek argues in a Comment, technological developments in both observations and analysis are revealing seismic heterogeneities of various sizes and with intricate internal structures in the lowermost mantle. Large low velocity provinces (LLVPs) and ultra-low velocity zones (ULVZs) are lower mantle structures where seismic waves move abnormally slowly relative to the surrounding mantle. Two LLVPs — the most prominent seismic features in the lower mantle — are situated beneath Africa and the Pacific Ocean[1]. They are hotter and compositionally distinct from the rest of the mantle and may contribute to upwelling plumes. In contrast, ULVZs are smaller features detected at the base of the mantle. As discussed in a Q&A with experts working on these ULVZs, their origin remains enigmatic: it is unclear whether they are persistent mantle features, temporary partial melts, or core–mantle reaction products that are continuously generated and transported away. Regardless of their origin, it is becoming clear that their location and structure are influenced by mantle convection processes.



Understanding the ULVZs remains difficult, even with a high-resolution seismic picture of the core–mantle boundary. ULVZs are often associated with partial melt linked to thermal anomalies at the base of the mantle[1]. However, some ULVZs are situated far from the hottest parts of the lowermost mantle, suggesting short-scale compositional heterogeneity in the lowermost mantle[2]. It has been suggested that the anomalous seismic velocities in the lowermost mantle can result from globally distributed, heterogeneous accumulations of subducted material[2]. This may mean that ULVZs and other lower mantle anomalies are part of the large-scale mantle convection cycle.

The key to unlocking the origin of ULVZs and their role in the dynamical evolution of the Earth's interior may lie in their link to mantle convection. In an Article in this issue, Wolf and colleagues report an ULVZ beneath the Himalayas. They show that this ULVZ is affected by south-westward mantle flow, indicated by strong seismic anisotropy — or a directional preference in seismic wave propagation — in the surrounding lowermost mantle. They attribute this to remnants of a subducted slab impinging on the core–mantle boundary. Although it is unclear whether this slab-driven mantle flow is ongoing or historic, it suggests a connection between ULVZs and plate tectonics.

The distribution and location of the ULVZs also provide insights. Most previously identified ULVZs are located in the interiors or at the edges of the LLVPs. However, in an Article in this issue Su and colleagues report ULVZs in otherwise high-velocity areas. Supported by geodynamic simulations, they suggest that oceanic crust sinking into the lower mantle may accumulate on the core–mantle boundary, where it could partially melt. This partially molten oceanic crust could migrate along the core–mantle boundary to form ULVZs in the high velocity lowermost mantle, as well as near LLVPs.

The studies of ULVZs presented in this issue are additional pieces of evidence that no part of the silicate Earth is left untouched by plate tectonics. Seismic tomography offers an observational window — albeit an indirect one — to these enigmatic structures. Together with mineral physics and numerical simulations, further seismic tomographic imaging is key to better understanding the thermal and chemical state of the lower mantle.

References

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